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STATUS OF THE NASA-LEWIS RESEARCH CENTER SPACECRAFT CHARGING INVESTIGATION

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ABSTRACT

The Spacecraft Charging Investigation in the USA is being conducted under a joint, interdependent USAF and NASA program. The objectives of this investigation are to develop the technology necessary to control the absolute and differential charging of spacecraft surfaces. As the NASA lead center for this program, the Lewis Research Center (LeRC) has responsibility for developing ground simulation facilities, characterizing the charging and discharging characteristics of spacecraft materials, developing analytical modelling tools and issuing the design guidelines documents which are the principal output of the joint investigation. The development of analytical modelling is proceeding with the NASA Charging Analyzer Program (NASCAP). Facilities have been developed and testing of various materials completed. Comparisons between the experimental results, space results and predictions from models have been and are being made. Harness transient monitors have been flown on satellites. Status reports on the various parts of the LeRC investigation are included in this report.

Keywords: Spacecraft charging, Environmental interactions, Materials behavior

1. INTRODUCTION

Since the early 1970's there have been an unusually large number of anomalous events occurring on geosynchronous satellites (Refs. 1-2). These events have ranged from uncommanded electronic switching to complete failure of a power system. While unexplained changes in logic states of electronic systems were annoyances, they were correctable. The loss of a power system, such as that which occurred on a DSCS II satellite in 1972 (Ref. 2), meant the termination of that mission. This catastrophic failure provided the impetus to determine the cause of and to develop the techniques for preventing anomalies.

A plausible cause of the anomalies was found in the Applications Technology Satellite's (ATS-5) Auroral Particles Experiment data. These results showed the existence of transient particle fluxes of higher-than-expected energies at geosynchronous altitudes (Refs. 3-5). When the satellite encounters this geomagnetic substorm environment, spacecraft structures can be charged to negative potentials as high as -19 kV during eclipse periods (Ref. 6). When the encounter occurs in sunlight, photoemission from the exposed, sunlit surfaces will keep the spacecraft ground potential to modest levels - usually only a few hundred volts negative. However, spacecraft structures have been found to charge to -2 kV in sunlight during encounters with severe substorms.

If a spacecraft structure can be charged to such levels, then it is conceivable that the insulator surfaces of a satellite can be charged to similar levels. A shadowed insulator can be charged to a voltage level substantially different from the structure or from another insulator that is illuminated. Hence, it is possible that large differential voltages can develop on a satellite encountering a substorm.

It has been shown in laboratory tests on typical spacecraft surfaces that, with large differential voltages, discharges can occur (Refs. 7-9). The resulting discharge will emit electromagnetic pulses which can couple into the spacecraft harness. The low-level logic used in most satellites is susceptable to disruption by discharge-generated electromagnetic interference. Therefore, it is possible that environmentally induced discharges can be the cause of anomalies observed on geosynchronous satellites.

If the anomalies are caused by discharge-generated pulses in spacecraft harnesses, then one suggestion to minimize anomalies is to add filters to eliminate the transient pulses (Ref. 10). Apparently, this approach did work on the Canadian-American Hermes Satellite (Ref. 11).

Satellites being developed for future missions will require lifetimes greater than 10 years. While filtering may provide the immediate answer for preventing electronic anomalies, it does add weight. Whether or not the new, long life satellites can tolerate the added weight still has not been determined, but designers would appreciate not having to carry such penalties. Furthermore, filtering only prevents switching anomalies, it does not stop the charging and discharges. If discharges continue, degradation of thermal control surfaces can occur that can be serious on long term missions. The electric fields resulting from surface charging could enhance electrostatic contamination, further complicating thermal designs. The effects of long time electrical stresses in insulators from the deposited charge have not been evaluated, but they could impact

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satellite lifetime. Therefore, it was decided that corrective measures for controlling the effects of charging of spacecraft surfaces by environmental fluxes should be found.

In 1975 the USAF and NASA undertook a joint investigation of the environmental charging phenomenon (Ref. 12). The objective of this investigation is to provide the design guidelines, materials and test methods to insure control of absolute and differential charging of spacecraft surfaces. The Lewis Research Center (LeRC) was assigned the lead NASA responsibility in this investigation. In this report, only the elements of the LeRC study are discussed. The USAF role is defined in Reference 12.

2. LeRC SPACECRAFT CHARGING INVESTIGATION

2.1 Program Elements

Under the joint USAF/NASA Spacecraft Charging Investigation, the LeRC is responsible for both ground technology and space studies. The program that has been established at the LeRC to conduct this investigation is illustrated in Figure 1.

The LeRC investigation is structured around two main elements; the analytical modelling tool called NASCAP (NASA Charging Analyzer Program) and ground test facilities. The analytical modelling tool is a computer simulation of the charging phenomenon capable of treating both ground test and space conditions. Ground testing is conducted in the LeRC facilities to understand how the various spacecraft surfaces respond to simulated environment fluxes. These results are compared to analytical predictions to calibrate the modelling tool.

Spacecraft harness noise monitors have been developed and flown on both the Hermes-Communications Technology Satellite (CTS) and the Orbital Test Satellite (OTS). These monitors measure the transient responses from surface discharges that couple into spacecraft harnesses. The results can be used to aid in the understanding of spacecraft response to environmental fluxes. The CTS monitor data will be discussed later in this report.

The output of the Investigation is to be a Design Guideline Monograph. This document will summarize the knowledge of spacecraft charging phenomena and will present guidelines to be used to control the absolute and differential charging of spacecraft surfaces. The monograph will incorporate the results of both the LeRC and USAF investigations. The initial version will be issued by October, 1978. It will be updated after the SCATHA (Spacecraft Charging At The Altitudes) mission in 1979 and reissued by late 1980.

2.2 Analytical Modelling Computer Program

The analytical modelling tool developed for this investigation, NASCAP (Refs. 13-15) is capable of simulating the charging of 3-dimensional, complex bodies as a function of time for either ground test or specified space environmental conditions. The material properties of the surfaces are included in the computations. The surface potentials, potential distributions on the surfaces and in space and particle trajectories are calculated.

The flow diagram for the program is shown in Figure 2. The various program elements will be described briefly in the following paragraphs. A detailed description of the program can be found in the literature (Ref. 13).

2.2.1 Program set-up: The computer model is set up in an embedded mesh, 3-dimensional network (see Fig. 3). The spacecraft is described in the inner mesh region which is currently limited to 17- by 17- by n points where n can be any integer up to 33.

The space surrounding the spacecraft model is defined in a series of cascading outer mesh regions. Each outer region is double the size of the adjacent inner region. This cascading is to reduce computational time. At the outermost boundary, undisturbed environmental parameters (which can include sunlight) are specified.

2.2.2 Object definition. - The object can be a geometrically complex spacecraft model or a simple plate. In either case, the object must be constructed of cubes or sections of cubes. Curved surfaces are not allowed, but can be approximated by sections of cubes.

The surfaces can be bare metal or covered by a thin dielectric film. At present material properties of aluminum and magnesium for structures and Teflon, Kapton, and Quartz for dielectric coverings are stored in the program code. Other materials can be used but their material properties (secondary emission, backscatter coefficients, photoemission and resistivity) must be specified.

A graphical output of the object can be obtained. The computer will provide isometric or planar views of the object defined from any set of axes requested. In addition, this graphical display will code the surface materials specified for each cell. Since some objects can be complicated, this option can save valuable computer time by insuring that the object being analyzed is the one desired.

2.2.3 Computational elements. - Trajectory calculations are conducted to determine the incoming flux of particles. There are three basic operational modes for these calculations: forward trajectory calculations (for ground test conditions) and either "reverse particle pushing" trajectory computations or Maxwellian environmental approximations (for space conditions).

Surface interactions are computed to determine charge distributions on the spacecraft surface. The processes considered are secondary emission due to both electron and ion impacts, backscatter, photoemission and leakage through the material. Surface conduction between adjacent cells is not presently considered. The code will compute space charge due to secondary and photo emitted electons in the region adjacent to the spacecraft.

A conjugate gradient computation technique is used to determine surface potential distribution as well as potential distribution in space. The program assumes that there are no space charge effects except adjacent to the spacecraft model (when that option has been selected).

The program will iterate on these computational elements until a self-consistent solution is obtained. It has been found that 60 iterations are sufficient to obtain a valid potential distribution for a time step.

2.2.4 Output. - For each time step (if desired), a printout can be obtained of the charge or potential throughout the embedded mesh network. Graphical outputs of potential contours and particle trajectories in the plane of any combination of axes can be requested.

2.2.5 Status. - The NASCAP code is currently operational on the LeRC UNIVAC 1100 computer. Both ground test simulation and space model routines are being checked out. A User Manual (Ref. 16) is available.

2.3 Ground Test Facilities

A geomagnetic substorm simulation facility has been developed at the LeRC to conduct the materials response investigations (Ref. 17). This facility is housed in a 1.8 m diam by 1.8 m long vacuum chamber capable of operating in the 10^{-7} to 10^{-8} torr range. The facility is shown in Figure 4 and a schematic diagram is given in Figure 5.

2.3.1. Environmental Simulation: The electron content geomagnetic substorm flux is simulated by an electron source. This source can be operated as a monoenergetic beam at any accelerating energy between 2 and 25 kV or as a distributed energy beam cycling over wide energy ranges (500 to 25,000 volts) about once per second. In either case, the current density over a 3000 cm^2 area can be controlled at values between 0.5 and 5 nA/cm^2.

Solar simulation can be obtained from a Xenon lamp simulator. This simulator is located outside the chamber and the illumination is transmitted through a quartz window.

Low energy plasmas are generated in the chamber by means of a gaseous nitrogen electron bombardment plasma source. This source is routinely used to discharge sample surfaces after testing.

2.3.2 Test Specimen: Samples to be tested are mounted on a three-position sample rotator. Up to three different samples can be tested during each pumpdown of the facility. Samples up to 30 by 30 cm in size can be accomodated. Substrates of the test specimen can either be grounded, allowed to float electrically or be biased by external power supplies.

2.3.3 Instrumentation: Electron current density at the test location is measured with a Faraday cup. This cup is mounted on a 30 by 30 cm plate which shields the sample while the gun parameters are being established.

The surface voltage of the sample is measured by sweeping the electrostatic voltmeter probe across the sample. This probe is a noncontacting capacitance coupled device and usually traverses the sample about 3 mm above the surface. The probe functions while the beam is on so that continual charging curves can be obtained without interrupting the electron flow.

When the test sample substrate is grounded, the total leakage current through the dielectric and around the sample edges is measured by an electrometer in the ground line. From these data the charge stored in the test samples can be determined. Typical data sets for materials characterization tests are shown in Figure 6.

When discharges occur additional measurements are taken. Loop antennas are used to sense and quantify discharge activity. The signals received by the antennas are amplitude discriminated into 3 separate ranges (> 1 V, > 2.5 V, and > 5 V) and counted. Inductively coupled current probes on the sample ground line (with the current sensing electrometers switched out) and fast oscilloscopes are used to measure the replacement currents resulting from arcs. This measurement allows the computation of charge being drawn from ground to neutralize image charges in the test sample. This replacement charge can then be compared to the charge lost during a discharge as computed from leakage current transients and surface voltage measurements.

Discharges are photographed with a Polaroid portrait camera. These photographs can be either multiple exposure to obtain the complete discharge history of a given test or a single discharge exposure.

2.4 Material Characteristics

The majority of the testing has been done with monoenergetic electron beams with the sample substrate grounded. A listing of the surfaces tested is given in Table I. In addition to the single surfaces, multiple specimen samples have been evaluated to determine geometry effects on the surface charging. Rather than attempting to discuss all of the data, selected examples will be used to illustrate the status of the investigation.

2.4.1 Charging Studies. - The categories of samples to be discussed in this section are smooth surfaced insulators and rough surfaced insulators.

(a) Smooth surfaced insulators. - This cateis typified by insulators such as silvered Teflon or aluminized Kapton. When exposed to monoenergetic electron beams, the dielectric surface charges to a surface potential equal to the beam potential less the second unity yield voltage for secondary emission (Ref. 13) for silvered Teflon samples, this means that the surface voltage is about 1900 volts less than the beam voltage while for aluminized kapton, the surface potential is about 1200 volts less.

A given sample charges to equilibrium much like a capacitor in a finite period of time. This time can vary between 4 and 15 minutes depending on the material. When steady-state is reached for a given beam voltage, the surface voltage profile indicates strong gradients at the edges and a uniform potential at the center. Typical data for 5 mil silvered Teflon samples are illustrated in Figure 7.

Analytical models of the silvered Teflon samples have been developed using one dimensional approximations. These models have been used in conjunction with experimental data to obtain best-fit model parameters (Ref. 18). The fit obtained is shown in Figure 8. As can be seen, the simple current balance approach used in the one dimensional model does adequately describe the charging process for single surfaces. However, for multiple insulator surfaces this approach is questionable since there is no provision for coupling between the various insulator surface voltages.

Analytical models have also been generated for silvered Teflon using the NASCAP code. The comparison of the predicted equilibrium surface voltage profile against the experimental results for electrically floating substrates is shown in Figure 9. The predictions agree reasonably well given that the NASCAP code do not include surface leakage currents and that the bulk currents through the insulator are small.

(b) Rough surfaced insulators. - This category of samples includes such insulators as silica cloth and graphite-epoxy composites. These samples have an irregular or porous surface.

When exposed to the electron beam, the surface voltage profile exhibits a nonuniform potential corresponding to irregularities in the surface (see Fig. 10). These samples charge to rather low potentials which appear to be leakage-current controlled. The surface voltage profile still shows the edge gradient and also shows very high field gradients within the material.

The graphite-epoxy honeycomb samples tested have indicated that construction and materials used have a primary influence on the charging behavior. Two samples were tested side by side. One sample used expoxy-impregnated graphite woven cloth while the other used unidirectional graphite-epoxy cloth. The woven cloth sample charged to appreciable levels while the unidirectional cloth remained at lower levels (see Fig. 11). The woven cloth sample also glowed in the high energy beam (see Fig. 12). The picture is a 63 minute time exposure of a test at 20 keV beam. The glow in the right hand sample is from the sample microdischarges that occurred during the test. There were no discharges counted by the loop antenna system during this test. Therefore, it is believed that this type of sample relieves the internal stress by small, glow type discharges. This behavior would produce noise but should not couple into the spacecraft command system and thereby cause anomalies.

2.4.2 Discharge studies. - When the spacecraft charging investigation began, the basic questions of the focus and propagation of discharges were unanswered. There were photographs of discharges (Refs. 19-20) and possible models to explain the discharge characteristics (Ref. 22). All that was known was that discharges occurred and that the transient current pulse had the "wrong" polarity, i.e., electron flow from ground to the substrate.

There has been progress in categorizing discharge behavior. Discharges observed in the LeRC tests (and at other facilities) are believed to be edge phenomena. The discharges are triggered at the insulator edge or at an imperfection and charge is then moved along ionized paths to the site (see Fig. 13).

This belief is based on the following experimental facts. First, it has been found that the surface voltage at breakdown is far less than the dielectric strength of the insulators. For example, 5 mil silvered Teflon samples have been found to discharge when the surface potential is about -12 kV. This amounts to a dielectric strength of only 2-1/2 kV/mil much less than the published values. Second, it has been found that discharges can be inhibited by shielding the edges of insulators from the electron beam with a grounded metallic frame (Refs. 22-23). Under these conditions the silvered Teflon samples exhibit dielectric strengths of 7 to 10 kV/mil before breakdown through the materials occurs. These results are more consistent with the expected bulk breakdown behavior.

The discharge appears to create plasma particles which are accelerated away from the specimen. Both positive and negative charges have been observed leaving the surface as a result of discharges (Refs. 9 and 23).

The experimental evidence from the discharge studies seems to support the concept that the discharges initiate at insulator edges or at imperfections where the electric fields are strong. The discharge process creates a plasma, and both positive and negative charged particles leave the surface. The surface voltage at the discharge site collapses inducing surface voltage gradients which can cause microdischarges along tracks on the surface. The replacement transient current pulse from ground to the substrate accounts for the net charge lost from the sample. This replacement current charge has been found to be less than the total charge lost by the surface (Ref. 20).

This model of discharges is not complete and additional studies are required to develop a comprehensive model. The experimental work must be coupled to analytical evaluations in order to be able to extrapolate to large samples in a space environment.

2.5 Space Experiments

In this program element there are two topics: analytical modelling and spacecraft monitor packages.

2.5.1 Analytical modelling. - The NASCAP code has the capability of predicting surface potentials for complex satellites in space environments corresponding to geosynchronous orbits. The evaluation of this part of the program is currently underway. Comparisons between NASCAP models of ATS-5 and 6 and SCATHA, and flight data will be made to ensure the accuracy of the predictions.

At this time only geometrically simple objects have been modelled in the space version of NASCAP (Ref. 14). A Teflon covered sphere subjected to a geomagnetic substorm and sunlight is shown in Figure 14. This figure illustrates the necessity of using multidimensional codes to analyze environmental effects. The field distribution is assymetric - the shade side fields extend beyond the terminator and create saddle points in the distribution on the sun side (Ref. 26). The existence of such saddle points have also been reported by others analyzing the charging of spacecraft (Refs. 27-28). Simple, lumped parameter models of spacecraft will not recognize the existence of such distributions. The influence of this assymetric field distribution will be evaluated.

2.5.2 Spacecraft monitor packages. - A spacecraft harness noise monitor, called Transient Event Counter (TEC), has been flown on the Hermes (CTS) Satellite and operated for a year (Ref. 24). An improved TEC has been included on the Orbital Test Satellite (OTS).

TEC is a small, lightweight electronic device which senses and counts electrical transients in spacecraft wiring harnesses. It can detect

harness transients which exceed 5 volts in amplitude at rise times of less than 0.3 μsec. Its purpose is to identify transients in the spacecraft wiring harnesses which can be attributed to spacecraft charging phenomena, that is, to discharge energy picked up by the harnesses which could cause switching of spacecraft logic circuits.

On the Hermes satellite three wiring harnesses were monitored: the attitude control instrumentation wire harness between the nonspinning Earth sensor assembly and the attitude control electronics assembly; the solar array instrumentation harness within the spacecraft body at the slip rings; and the solar array power harness within the spacecraft body at the slip rings.

The flight data obtained with the CTS monitor for the year's operation is shown in Figure 15. Note the large number of multiple discharges that have occurred. Numerous attempts have been made to correlate these transient events to geomagnetic substorm activity based on ground observatory data without success. The local time distribution of transient events is plotted for each TEC channel in Figure 16. This is a polar view of the Earth with a 24 hour local time scale superimposed. TEC transients for each channel are plotted at spacecraft local time of occurrence without concern for the number of transients. The radial distance is used to separate the transient events into 3 month intervals. This distribution of the events appears to be random; transients can occur any time. Even though there have been a large number of transients recorded, there have been no spurious electronic switching anomalies reported. This is believed to be due to the filtering employed in the command and data lines (Ref. 11).

One conclusion reached from the TEC monitor data is that the spacecraft probably reacts in a different manner from that one would expect from simple, small scale laboratory tests. The multiple discharge characteristic of this data would indicate that large insulator surfaces on spacecraft are not completely discharged at once, but lose the stored energy in a series of smaller discharges. This evidently saves the spacecraft system from having to absorb all the discharge energy in a single burst. Tests of full sized spacecraft in ground facilities are required to understand this behavior.

Another conclusion from the TEC data is that environmental sensors are required on the satellite in order to interpret the harness noise data. A set of monitors to accomplish this has been described in the literature (Ref. 25).

3. CONCLUDING REMARKS

A technology program is underway at the LeRC as part of the joint AF/NASA Spacecraft Charging Investigation. This program includes both experimental and analytical investigations.

Considerable progress has been made in understanding charging of single insulator surfaces. It has been found that the surface voltage of the insulator can be estimated from a current balance. The charging of multiple insulator surfaces can be predicted by use of computer codes such as NASCAP.

Discharges that have been observed in ground facilities appear to be between the charged surface and space. Both positive and negative particles have been detected from discharges. Additional work is still required to model the discharge process and to scale the discharge energy as a function of insulator area.

Testing of large scale models of spacecraft in vacuum facilities is needed to complete the investigation of satellite behavior in a charging environment. By conducting these tests it will be possible to learn how multiple insulator, complex geometry surfaces charge, where discharges occur, and how the discharge energy couples into the spacecraft structure. Flight data from missions such as SCATHA are required to verify the accuracy of ground test results.

The information gathered in the LeRC investigation and that gathered by A.F. Laboratory studies will be used in a Design Guideline document. This document will present guidelines to be used in future spacecraft designs to minimize the spacecraft charging interactions. It is planned to issue the interim document by October, 1978. The final version of the document will be issued after the SCATHA flight.

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TABLE I. - MATERIALS TESTED

Spacecraft Paints
- S-13G nonconductive paint
- Z-93 nonconductive paint
- Conductive paints

Insulating Films
- Silvered Teflon
- Kapton

Thermal Blanket Samples
- Kapton Outer Layer
- Quartz Cloth Outer Layer

Solar Array Segments
- Standard cells on fiberglass substrates
- Solar cells in flexible substrates
- Solar cells with conductive film coverglass

Graphite Epoxy Honeycomb

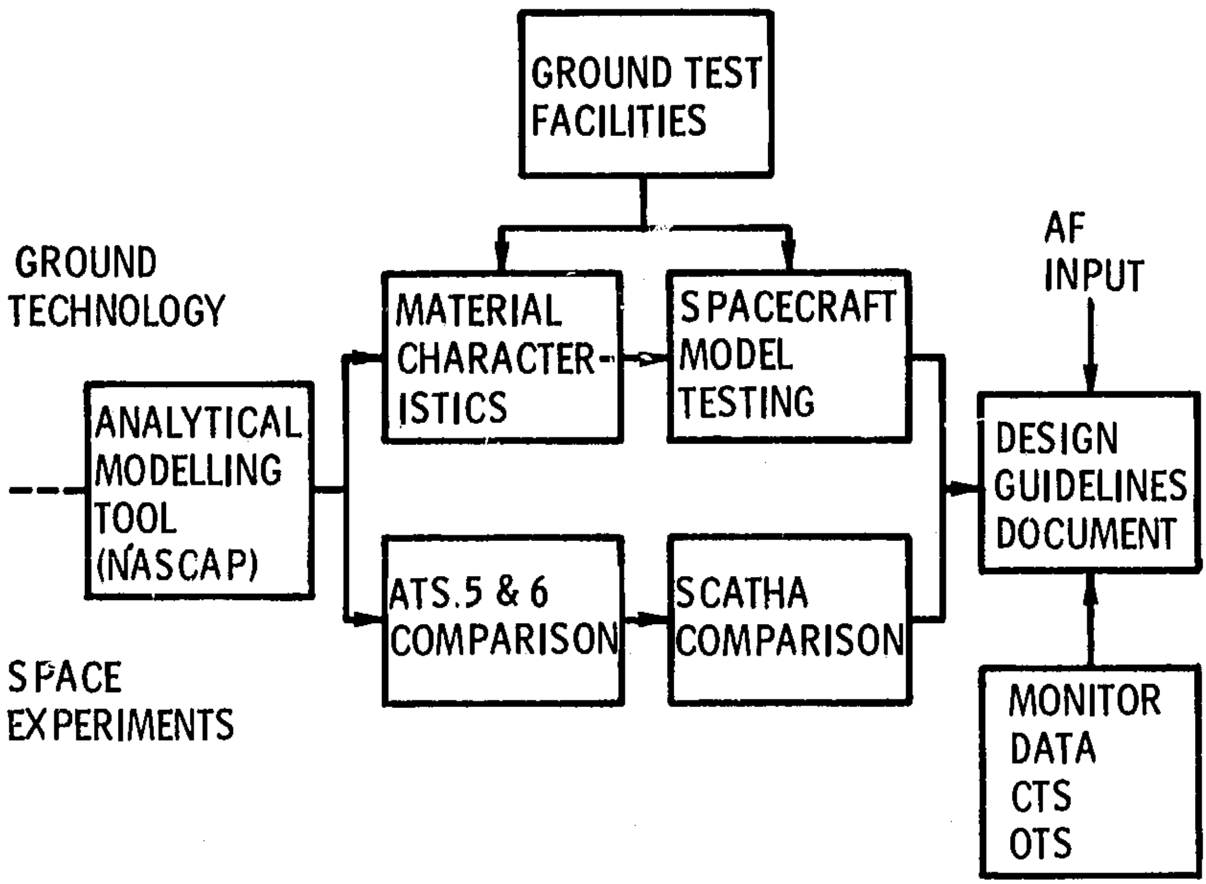

Figure 1. LeRC spacecraft charging investigation.

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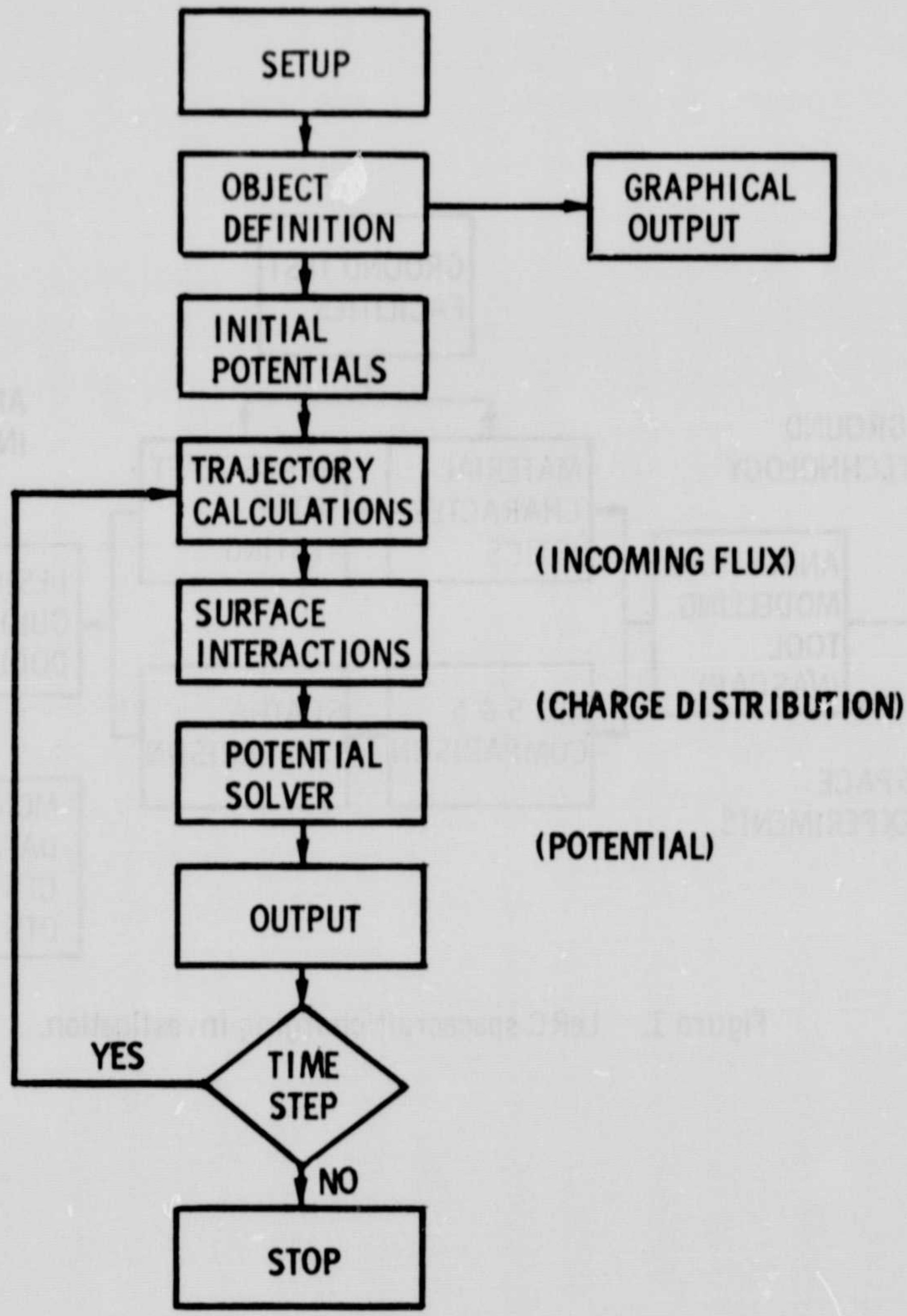

Figure 2. NASCAP flow diagram.

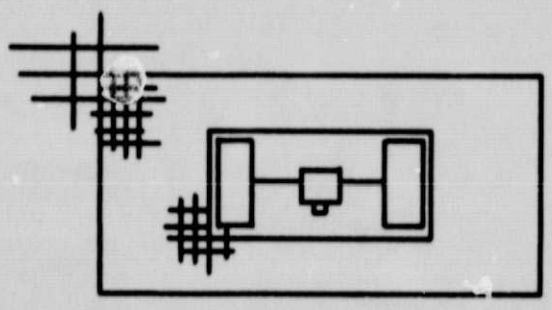

Figure 3. Cross-section (y-z plane) of grid, showing first three embedded meshes.

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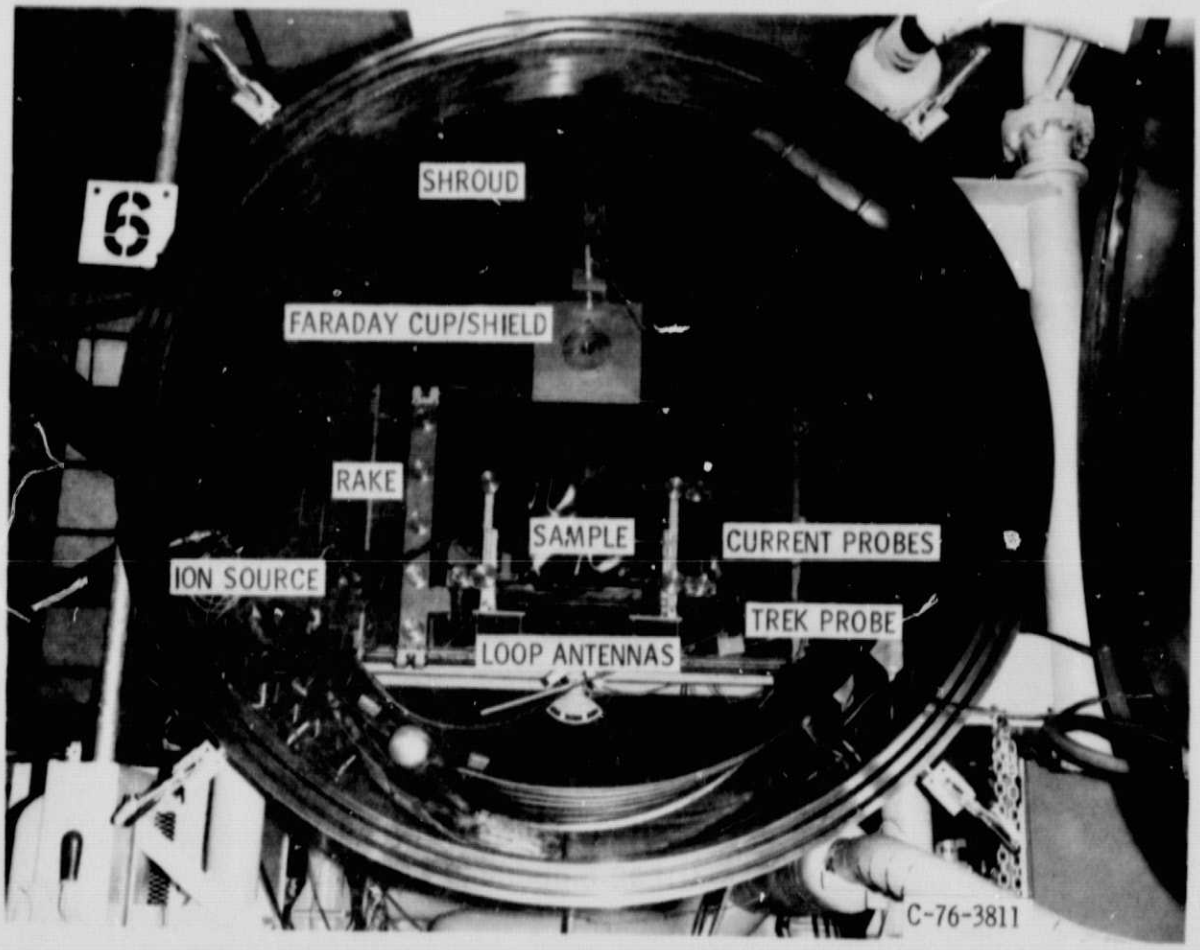


Figure 4. - LeRC Substorm Simulation Facility test chamber interior.

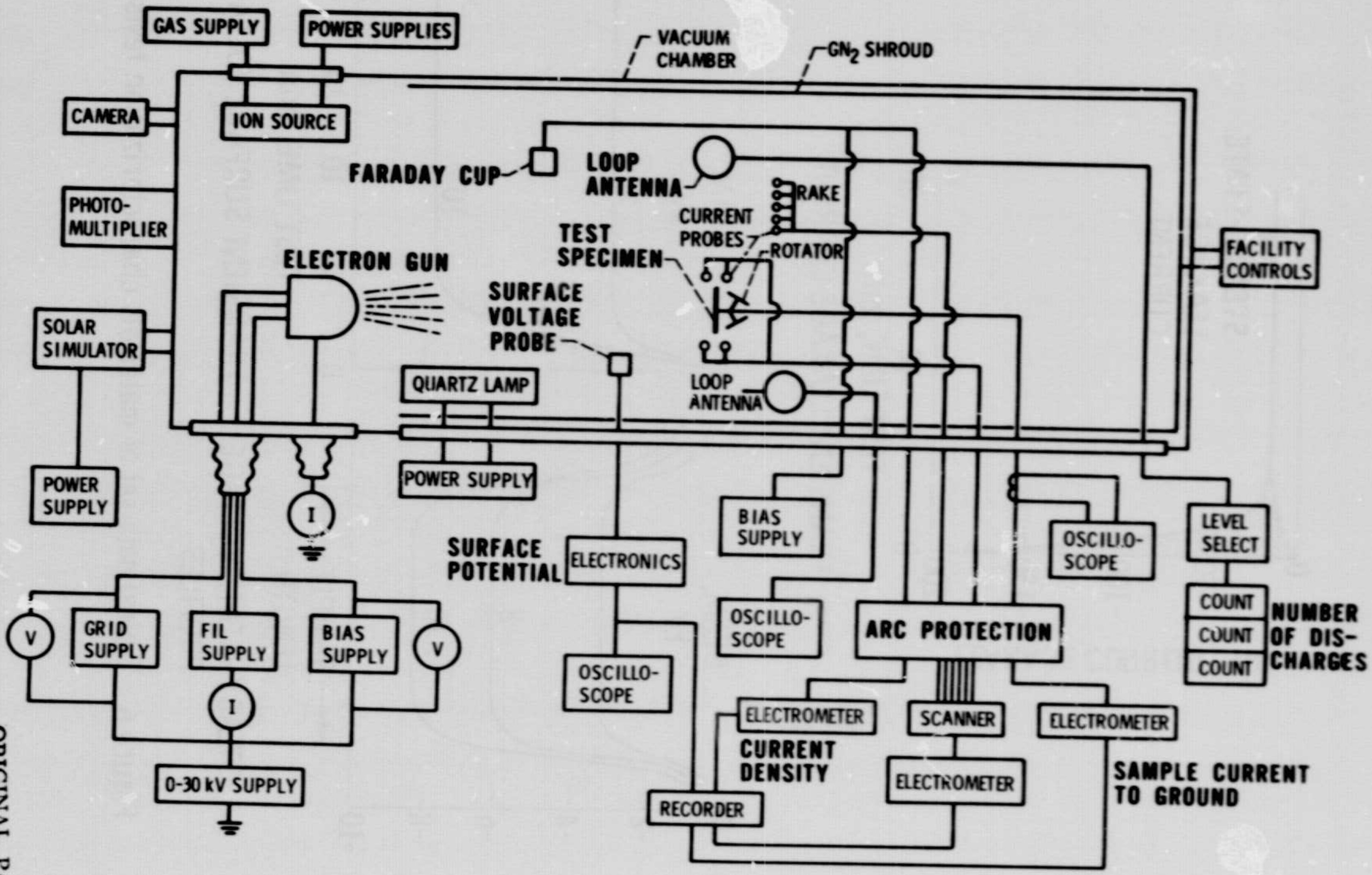


Figure 5. Schematic of the LeRC substorm simulation facility.

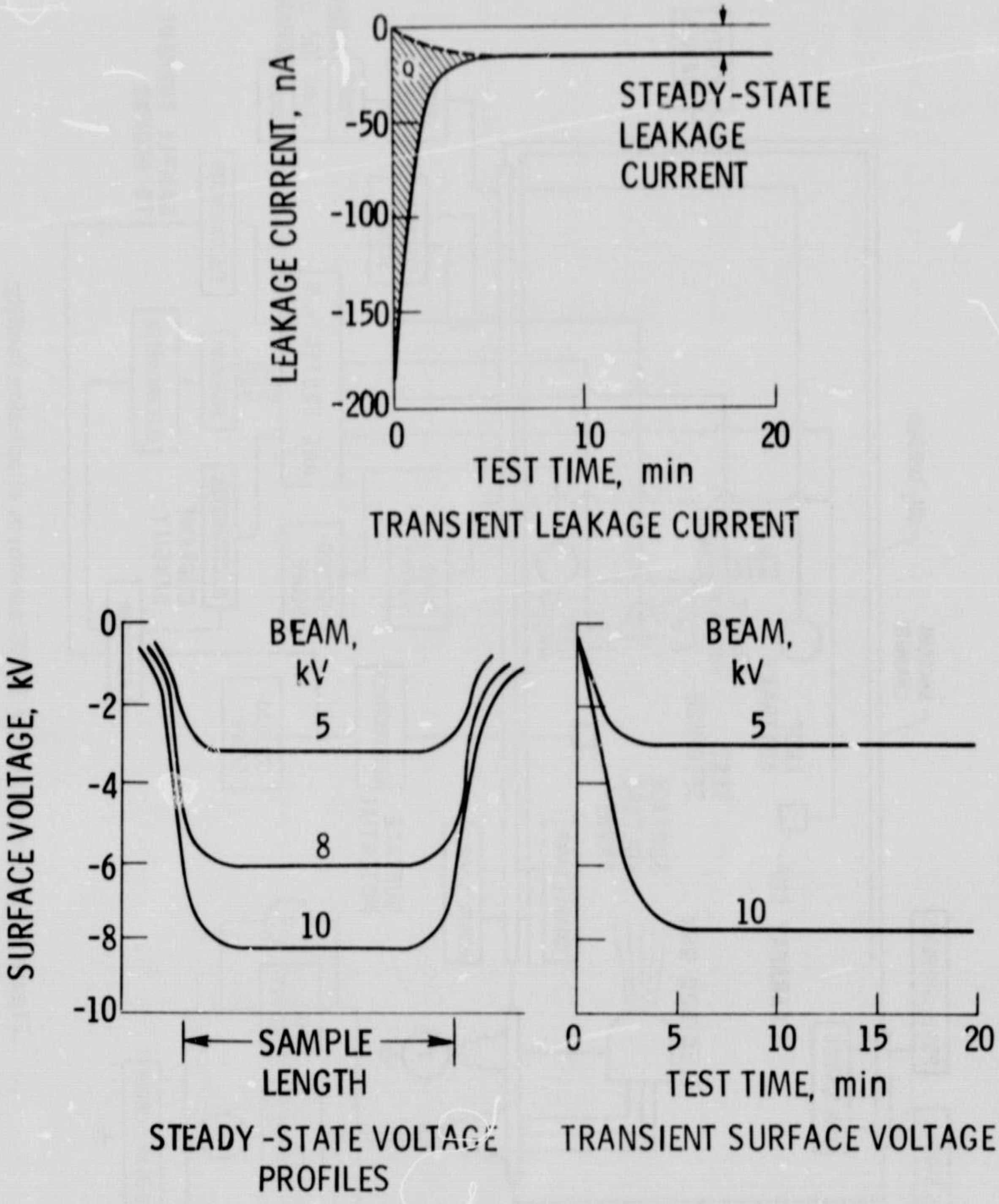
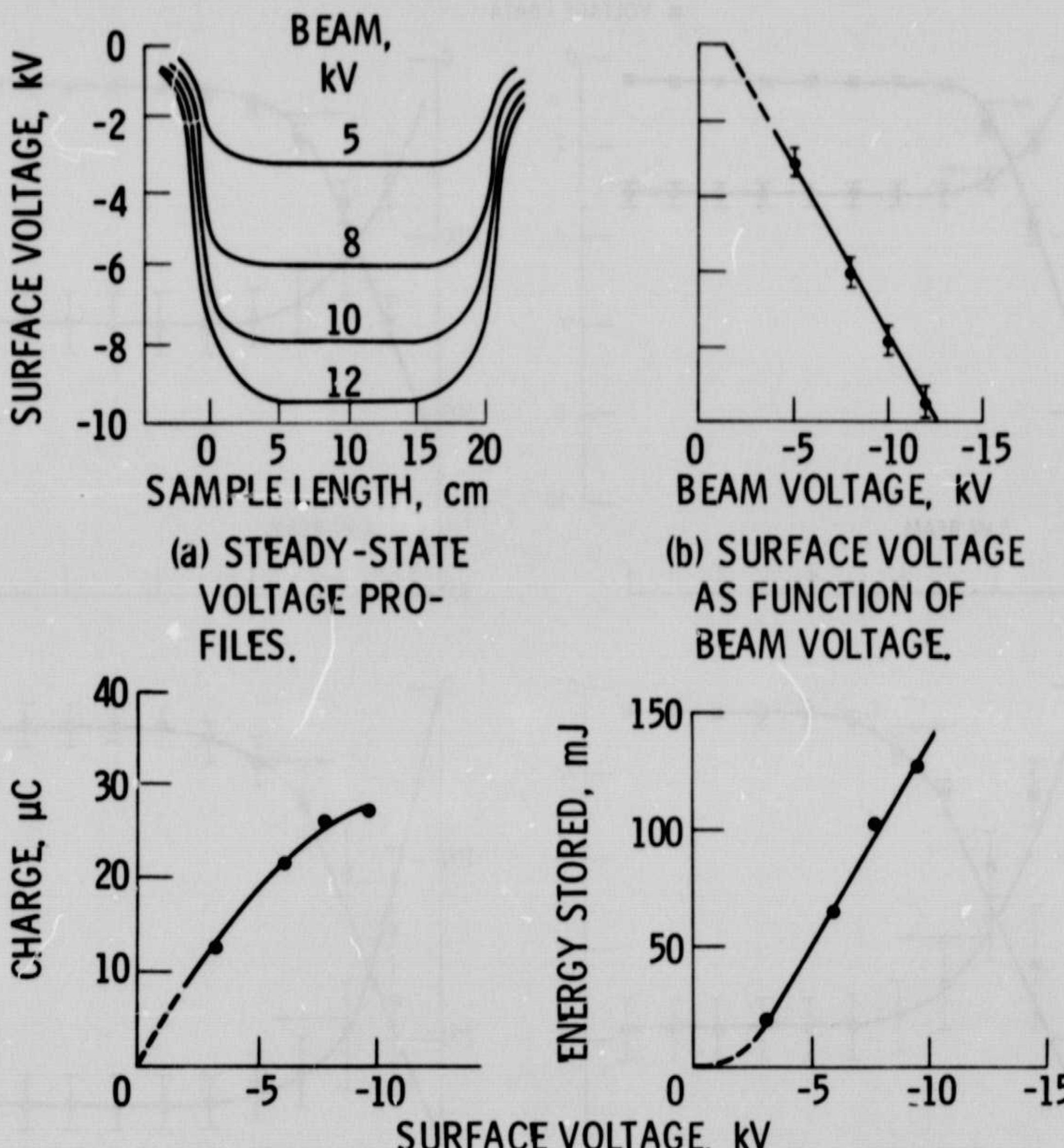


Figure 6. Typical data set of materials characterization tests.



(a) STEADY-STATE VOLTAGE PROFILES.

(b) SURFACE VOLTAGE AS FUNCTION OF BEAM VOLTAGE.

(c) CHARGE DEPOSITED.

(d) ENERGY STORED.

Figure 7. Silvered Teflon charging data.

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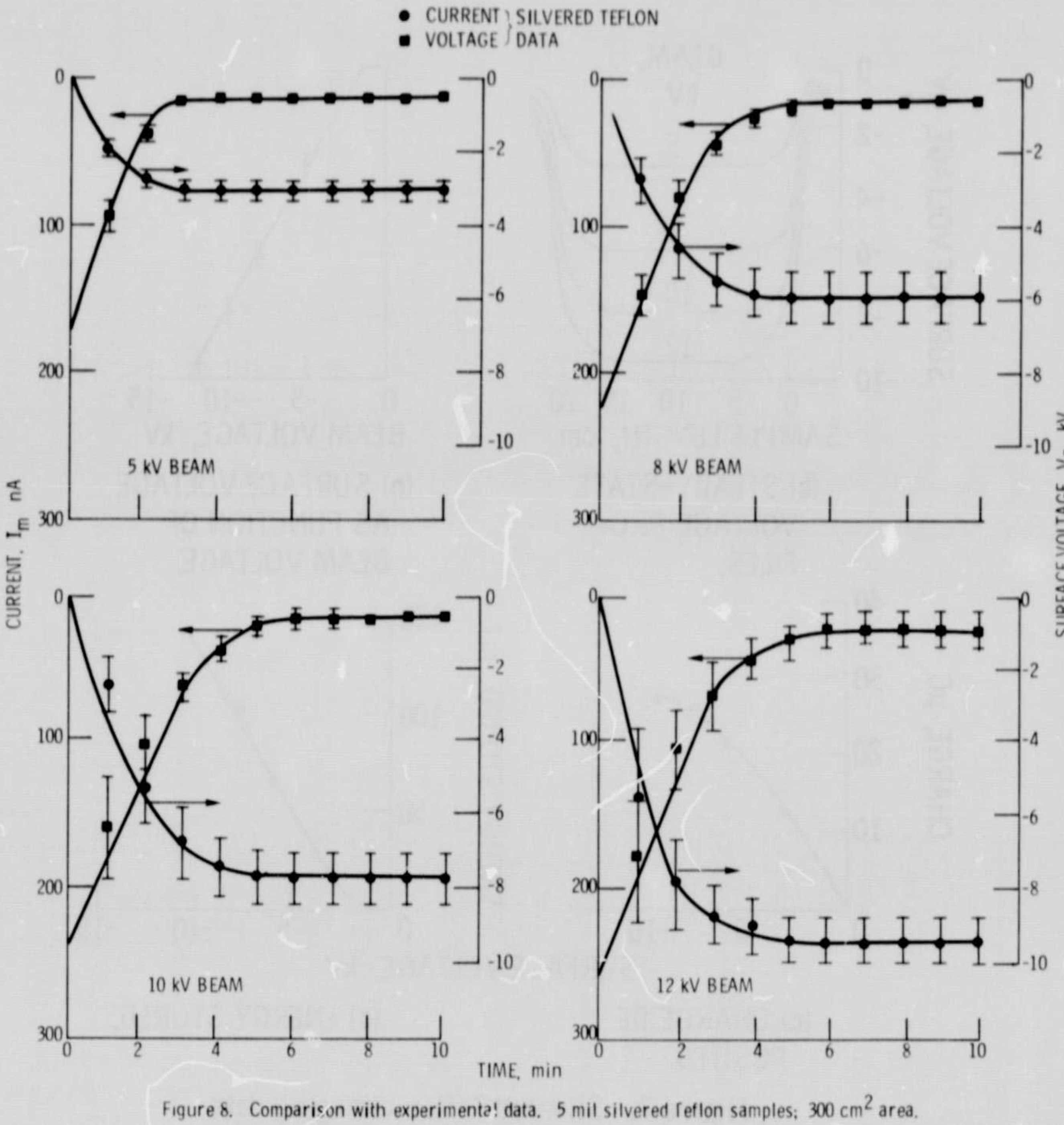

Figure 8. Comparison with experimental data. 5 mil silvered Teflon samples; 300 cm^2 area.

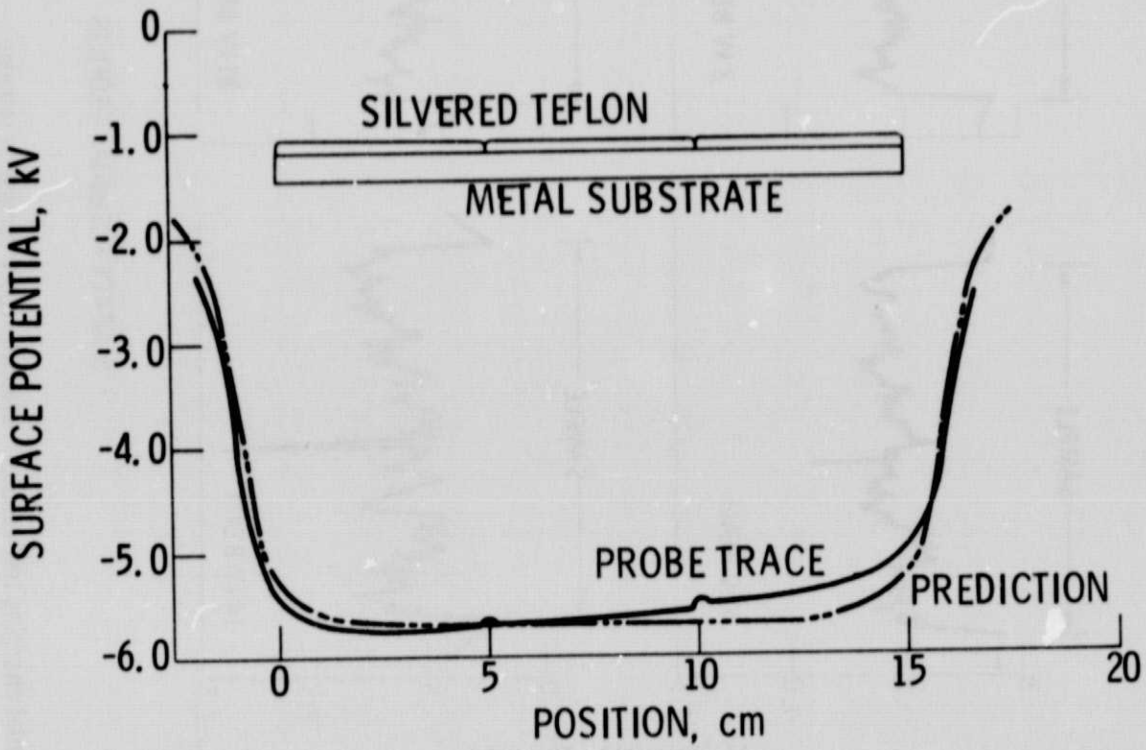

Figure 9. Comparison of NASCAP predictions with surface voltage profile substrate electrically floating (8 keV beam).

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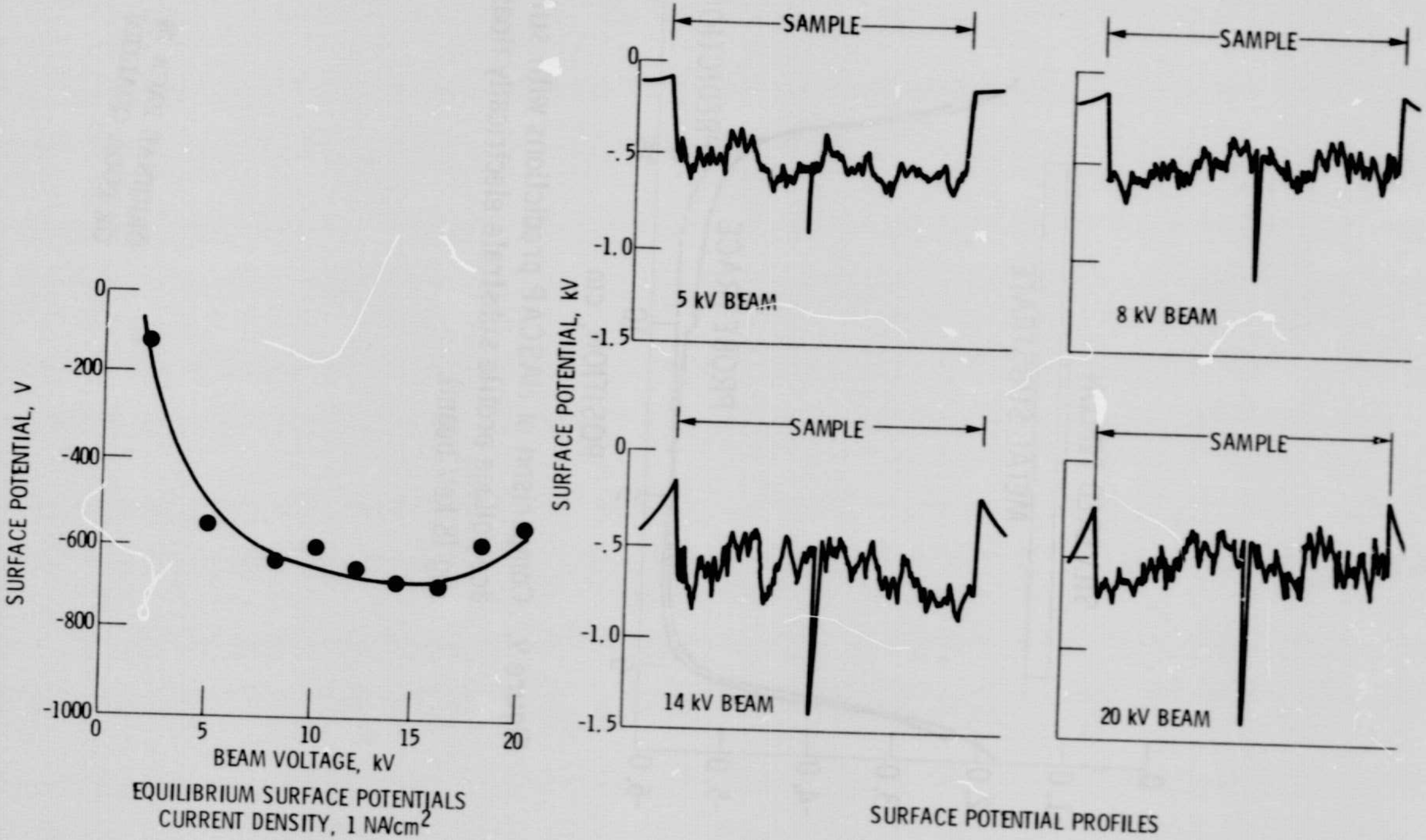

Figure 10. Environmental charging test results. Graphite-epoxy composite samples.

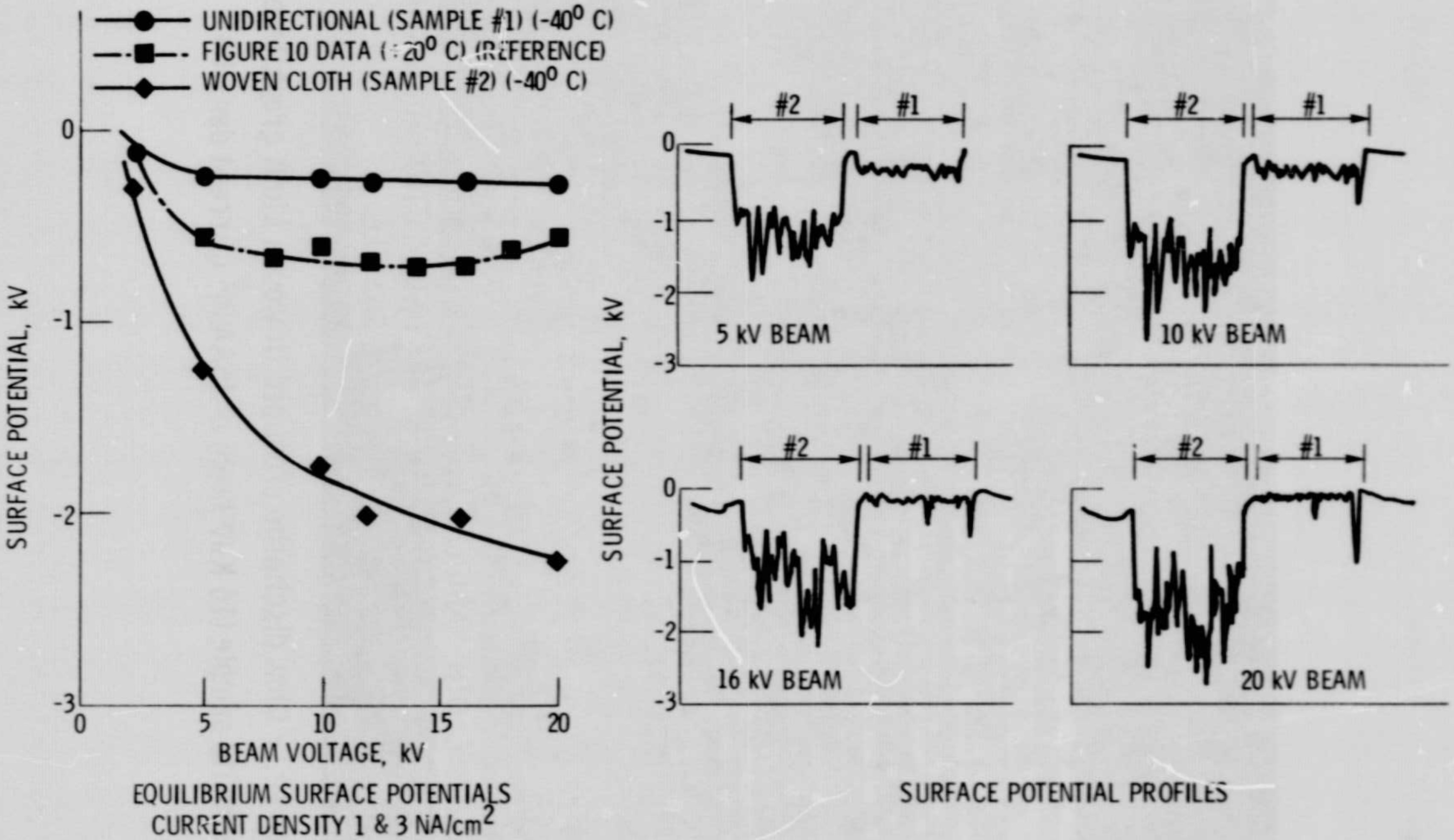

Figure 11. Environmental charging test results. Graphite-epoxy composite samples. Woven cloth and unidirectional cloth specimen.

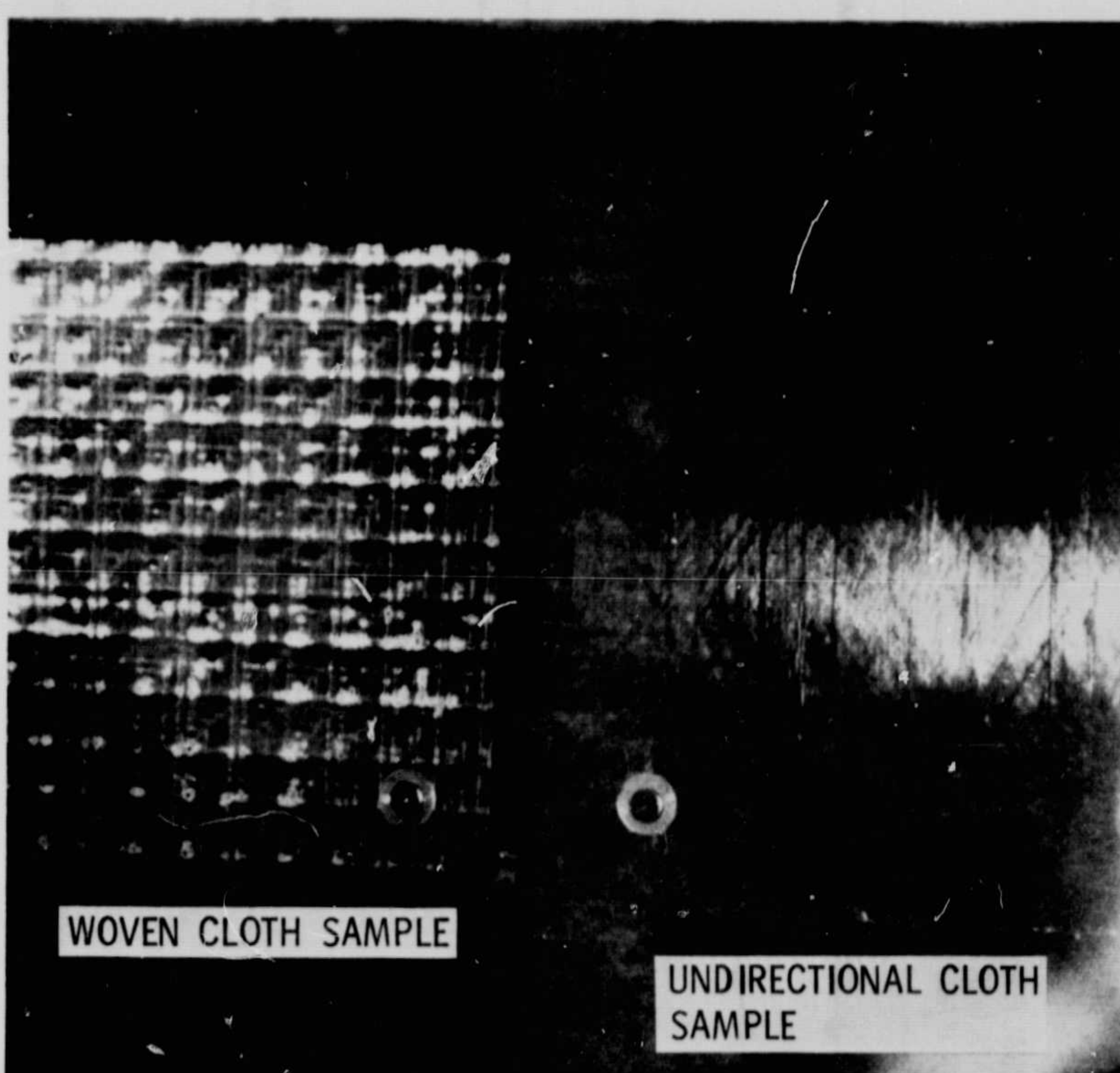

Figure 12. - Glow discharge produced in woven cloth graphite-epoxy composite sample (16 KeV beam of lnA/cm^2 current density).

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Figure 13. - Discharges in single sheet silver teflon sample.

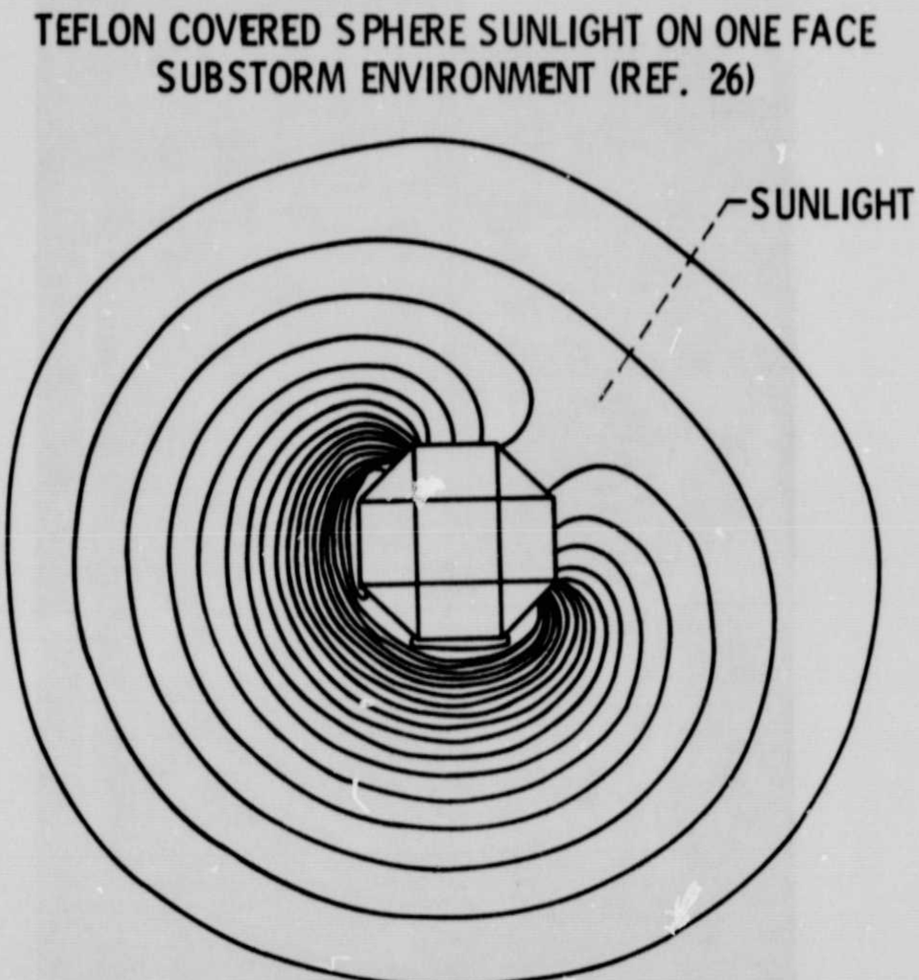

Figure 14. NASCAP predictions.

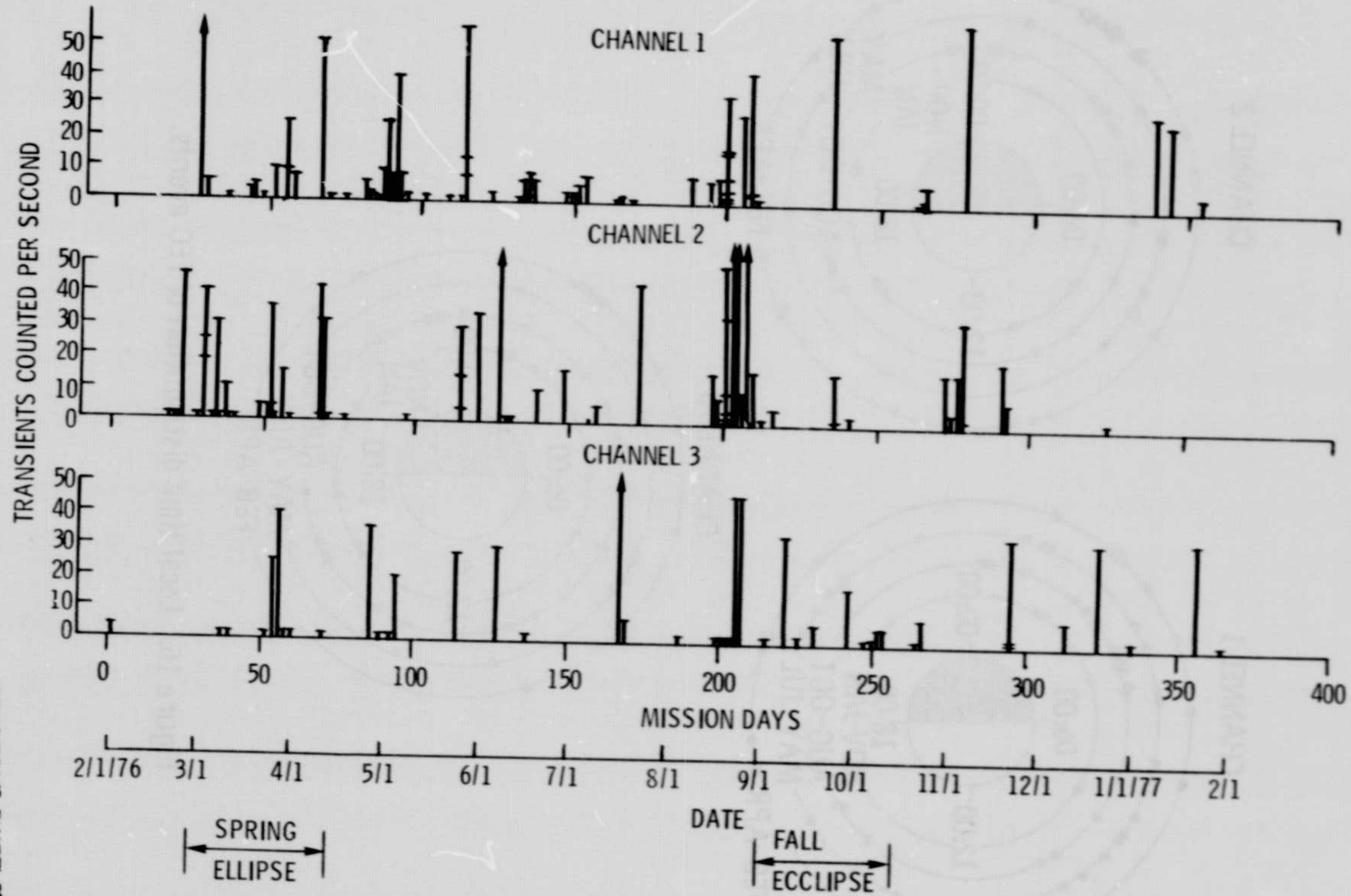

Figure 15. Summary of transient event counter data.

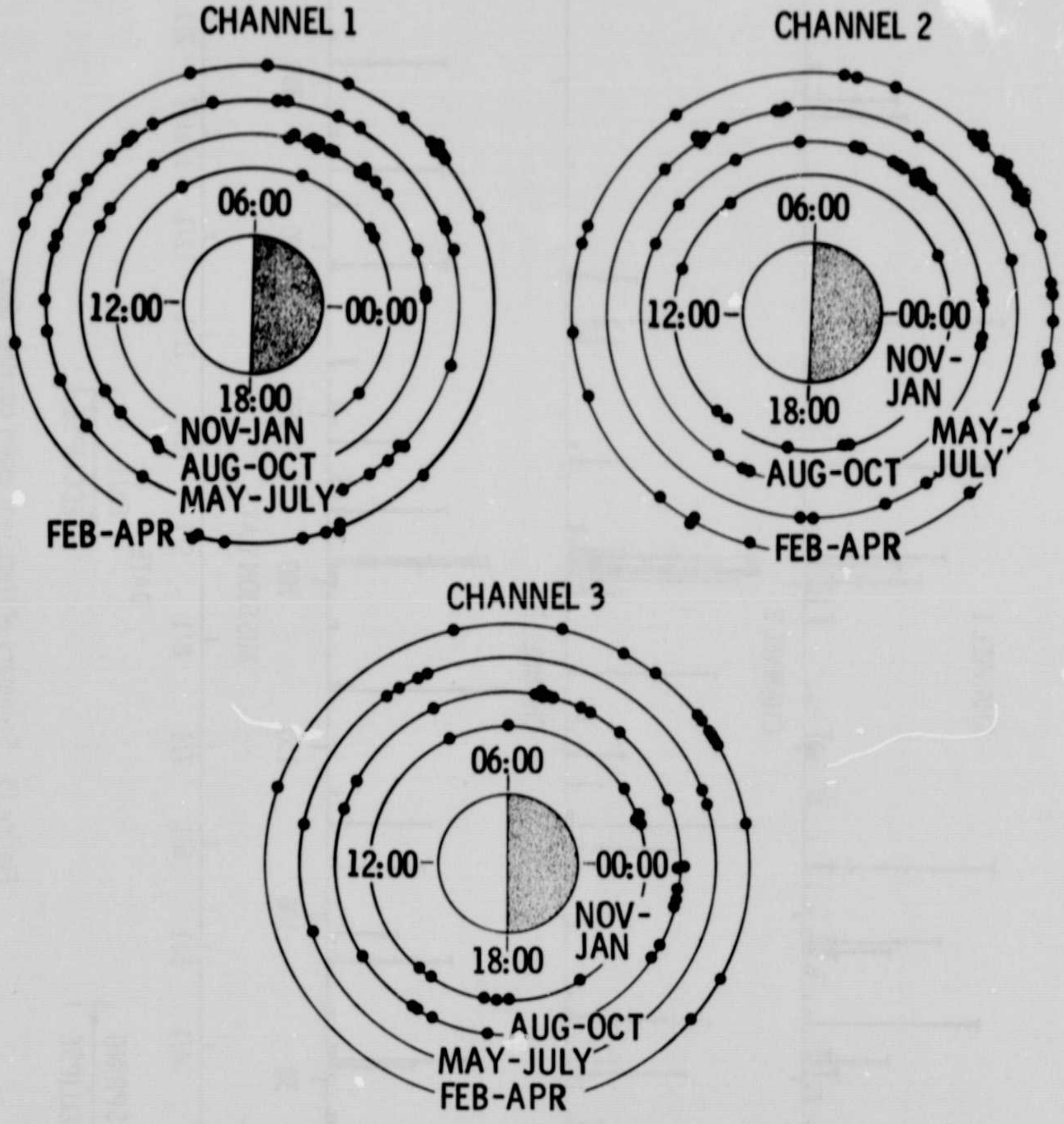

Figure 16. Local time distribution of TEC events.

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15. Supplementary Notes

16. Abstract

The Spacecraft Charging Investigation in the USA is being conducted under a joint, interdependent USAF and NASA program. The objectives of this investigation are to develop the technology necessary to control the absolute and differental charging of spacecraft surfaces. As the NASA lead center for this program, the Lewis Research Center (LeRC) has responsibility for developing ground simulation facilities, characterizing the charging and discharging characteristics of spacecraft materials, developing analytical modelling tools and issuing the design guidelines documents which are the principal output of the joint investigation. The development of analytical modelling is proceeding with the NASA Charging Analyzer Program (NASCAP). Facilities have been developed and testing of various materials completed. Comparisons between the experimental results, space results and predictions from models have been and are being made. Harness transient monitors have been flown on satellities. Status reports on the various parts of the LeRC investigation are included in this report.

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